Decadal-scale response of the Antarctic ice sheet to a warming ocean using the POPSICLES coupled ice sheet-ocean model

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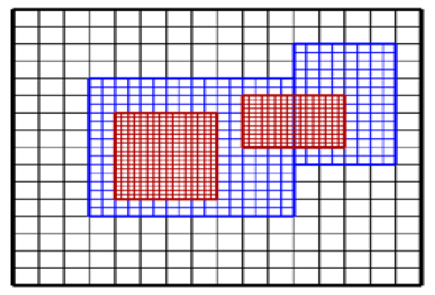
Motivation

One likely climate driver for marine ice-sheet instability is subshelf melting driven by warm(ing) ocean water intruding into subshelf cavities. Modeling this will require coupled ice sheet-ocean modeling in an earth system model (ESM), on multi-decadal to century timescales employing high spatial and temporal resolution. Target resolution for this work: Ocean: **0.1 Degree**, Ice sheet: **500 m** (using adaptive mesh refinement).

Numerical Models

Ice Sheet – BISICLES

- Very fine resolution (better than 1 km) is needed to resolve dynamic features like grounding lines and ice streams – computationally prohibitive for uniform-resolution studies of large ice sheets like Antarctica.
- Large regions where finest resolution is unnecessary – ideal application for adaptive mesh refinement (AMR).
- *Block-structured* AMR:
  - Refine in logically-rectangular patches.
  - Amortize cost of irregular operations over large number of regular structured-mesh operations.
  - *Finite-volume* discretizations simplify coarse-fine coupling.
  - Simplifies dynamic regridding to follow changing features.

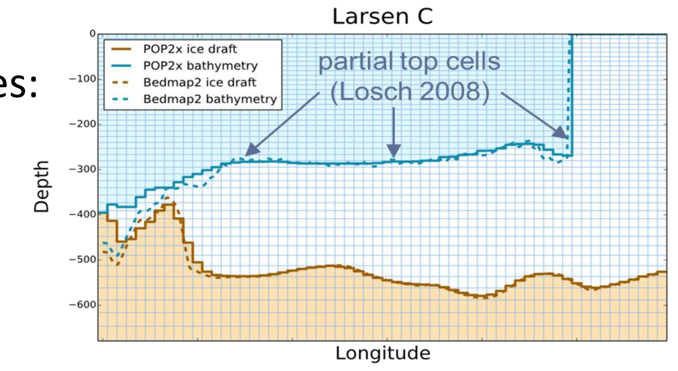


Sample AMR meshes – black mesh is base level (0), blue mesh (level 1) is a factor of 2 finer, while red (level 2) is 4 times finer still

- BISICLES is built upon the LBNL-developed Chombo AMR C++/Fortran framework, which supports scalable block-structured AMR applications.
- Modified version of the Schoof-Hindmarsh (2010) model ("SSA*")
  - Following Schoof and Hindmarsh, using SIA-like relation to compute stress allows vertical integration resulting in a simplified 2D nonlinear elliptic system for ice velocity at the bed.
  - Differ from standard L1L2 method by ignoring vertical shear when reconstructing flux velocities – reasonable approximation in fast-moving regions which improves numerical stability (SSA*).
  - Compares well with full-Stokes results in MISMIP3D experiments

Ocean Model – POP2x

- Ocean model of the Community Earth System Model (CESM)
- z-level, hydrostatic, Boussinesq
- Modified to include cavities under ice shelves:
  - partial top cells
  - boundary-layer method of Losch (2008)
- Subshelf melt rates computed by POP:
  - Methods of Holland and Jenkins (1999), Jenkins et al. (2001), and Losch (2008)
  - sensitive to vertical resolution
  - nearly insensitive to transfer coefficients, tidal velocity, drag coefficient



In POP, partial bottom cells discretize bathymetry. POP2x extends this approach to include partial top cells at upper ice-shelf/ocean boundaries, allowing computation of circulation in ice-shelf cavities.

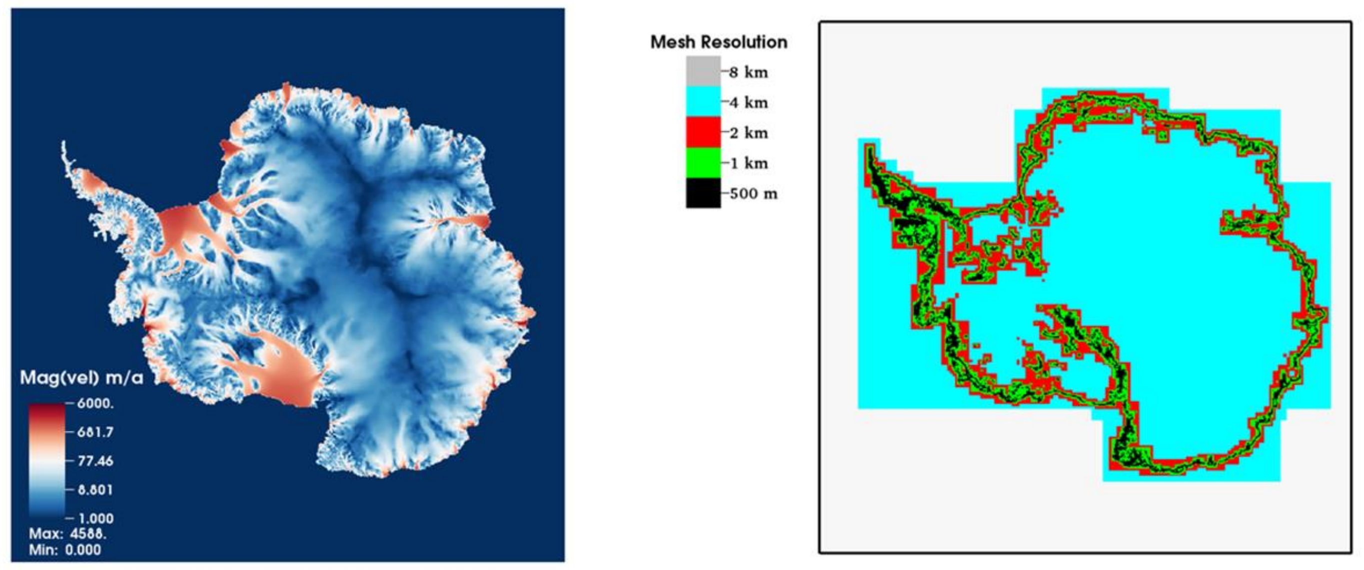
Coupling to POP2x through CISM

BISICLES is coupled to the Community Ice Sheet Model (CISM) as an external dynamical core, callable from CISM, which is coupled to CESM.

- Synchronous-offline coupling: BISICLES and POP exchange information at fixed coupling intervals.
- Monthly coupling interval arrived at through experimentation
- CISM-BISICLES → POP2x: Instantaneous ice draft, ice shelf basal temperature, grounding line locations.
- POP2x → CISM-BISICLES: Time-integrated subshelf melt rates
- Offline coupling using standard CISM and POP NetCDF file I/O.
- POP bathymetry and ice draft recomputed:
  - smoothing bathymetry and ice draft, thickening ocean column, ensuring connectivity
  - T and S in new cells extrapolated iteratively from neighbors
  - barotropic velocity held fixed; baroclinic velocity modified where ocean column thickens/thins

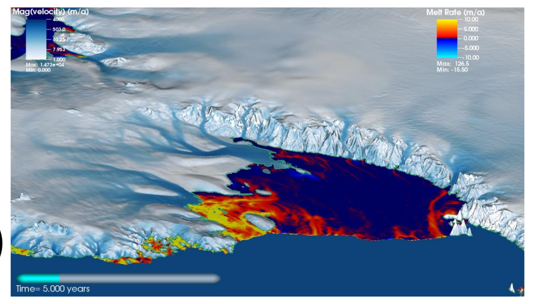
Coupled Antarctica-Southern Ocean

BISICLES Ice Sheet Setup



Movie frames showing Ice sheet initial condition: Initial basal velocity field (left), initial AMR meshes (right)

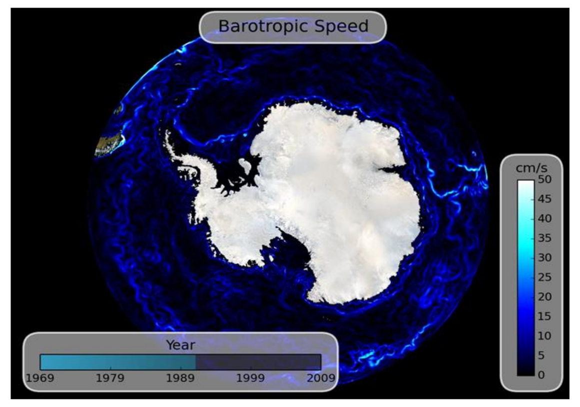
- Bedmap2 (2013) geometry
- Initialize to match Rignot (2011) velocity field.
- Temperature field from Pattyn (2010) spinup
- 500m finest spatial resolution (8 km coarsest mesh)
- Initialize synthetic accumulation field for equilibrium with POP melt rates computed in a standalone spinup run.



Movie frame showing subshelf melt rates painted on floating ice shelves in Ross sector,. Grounded ice coloring indicates the ice velocity.

POP 2x Setup

- Regional southern ocean domain (50-85°S)
- 0.1° (~5 km) horizontal resolution; 80 vertical levels (10m-250m)
- Monthly restoring to World Ocean Atlas (WOA) data at northern boundaries
- Climatology -- Common Ocean-ice Reference Experiments: (CORE) Interannual Forcing (CORE-IAF)
- 20-year standalone run to initialize
- Bedmap2 geometry for ice shelves and bathymetry



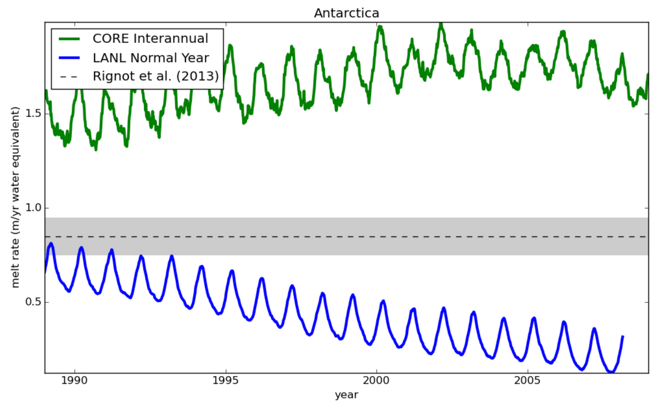
POP-computed barotropic ocean speed on Southern Ocean domain

Coupled Experiment

- 20-year experiment, ran standalone and fully-coupled
- Ran on NERSC's Edison machine -- 15,000 CPU-hours/simulation year

Experiment Results

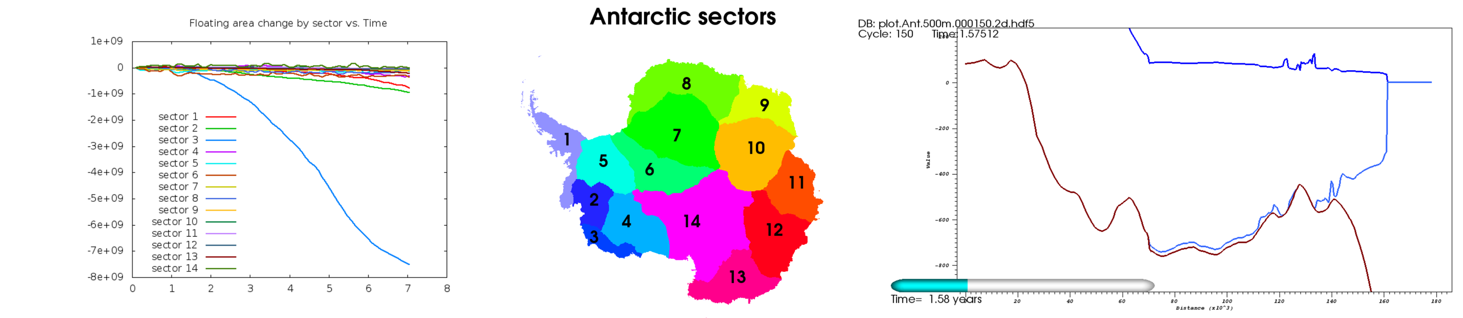
- Plot of integrated Antarctic subshelf melt rates compared to published values (Rignot et al 2013) at right.
- CORE-IAF produces too much melting (warm bias due to mixing of CDW into upper ocean, too much stratification from freshwater forcing – ocean model issue.)
- Response of coupled problem dominated by re-grounding instability in Getz sector.
- Other sectors: warm-water incursion leads to substantial grounding-line retreat.



Total Antarctic melt flux for CORE-IAF forcing (green), along with published value (Rignot, 2013).

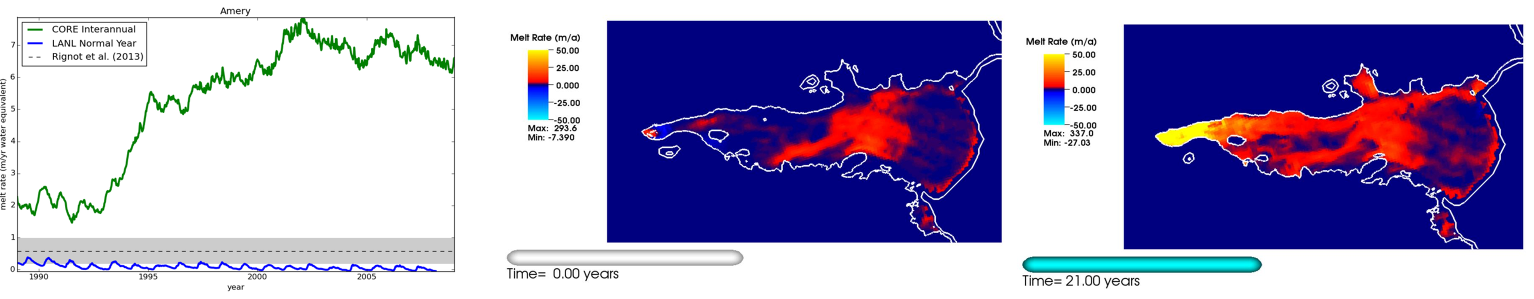
Getz Sector

- **Regrounding instability**: Artificially thin subshelf cavity combines with high melt rates to create instability – can see thickness fluctuations of O(subshelf cavity thickness), causing a localized regrounding event. Local regrounding removes subshelf melt component of the mass balance, resulting in large unbalanced accumulation, resulting in catastrophic regrounding. (Nonphysical artifact of artificially thin subshelf cavities in Bedmap2)



(left) sector-by-sector change in floating area vs. time. Note that regrounding in sector 3 (Getz) dominates. (center) Map of Antarctic sectors. (right) Movie frame of cross-section through Getz system showing regrounding around km 130; note artificially thin subshelf cavity.

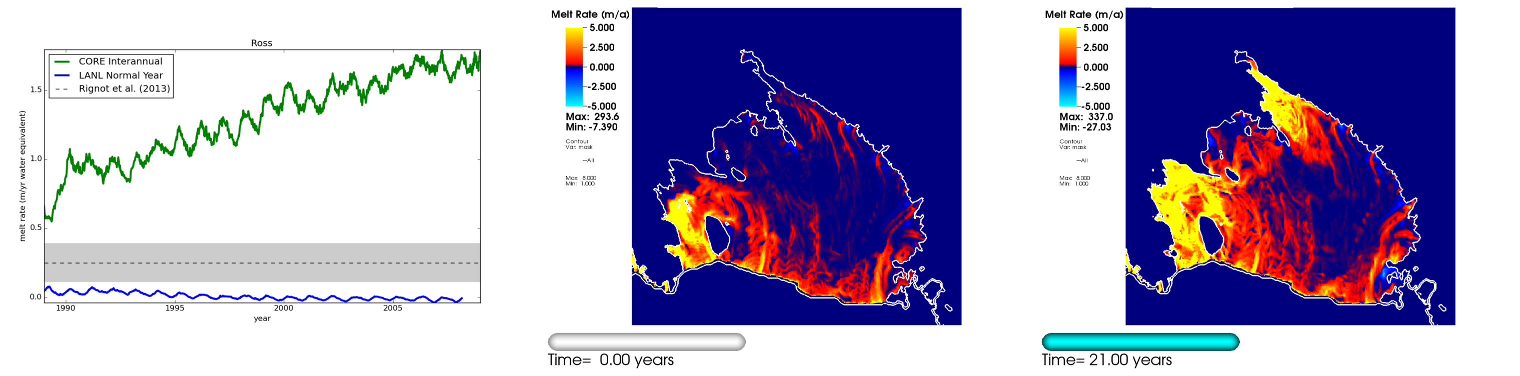
Amery Sector



***(left)** Integrated subshelf melt vs. time. **(Middle and Right)** Movie frames of instantaneous subshelf melt at initial time and after 20 years*

- **Warm-water incursion**: After ~5 years, warmwater pulse enters Amery system.
- In ~10 years, the warm water reaches the end of the Amery ice shelf, driving grounding-line retreat.

Ross Sector



***(left)** Integrated subshelf melt vs. time. **(Middle and Right)** Movie frames of instantaneous subshelf melt at initial time and after 20 years*

- **Warm-water incursion**: Initially more melting compared to Rignot values
- Initial melt primarily located near entrance.
- After 20 years, strong melting has reached rear of cavity.

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